1428682

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## (54) ELEVATION-MEASURING SYSTEM

(71) We, INTERNATIONAL STANDARD ELECTRIC CORPORATION a Corporation organised and existing under the Laws of the State of Delaware, United States of America, of 320 Park Avenue, New York 22, State of New York, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to a system for the measurement of elevation by the measurement of phase-difference.

A great number of systems for measuring the elevation are known which operate by the phase-difference method. These systems generally use 2 or 3 radiators. They are not very accurate and are susceptible to interference due to multipath propagation. Therefore, they are not suitable for landings according to categories II and III of the ICAO Standard.

The present invention provides a system for measuring elevation which uses the ground station apparatus proposed in our prior British Patent Application No. 3457/73 (now B.P.S. No. 1410121) and part of the airborne station proposed there, namely the equipment for measuring the phase and amplitude of each received r.f. pulse. Starting from that prior proposal, the present invention develops from the measured values so-called virtual patterns with shapes permitting the elevation to be measured as accurately as possible even at very small angles.

According to the present invention there is provided a system for the measurement of elevation by the measurement of phase-difference in which, at a ground station, n equally spaced radiators of a vertical linear antenna array cyclically and successively radiate r.f. pulses with equal magnitude and equal phase, one pulse train being radiated prior to each radiation cycle, and in which, at an airborne station, the phase and amplitude of the r.f. oscillations of each pulse in each cycle are measured relative to one of the pulses, at least two different groups being formed each containing m successive received pulses (where m<n), wherein, in each group, the phase and amplitude of each pulse are changed, the changes for corresponding pulses of all groups being the same, the vector sum of the changed pulses of each group is determined, and the elevation is determined from the phase difference of the said vector sums.

In one embodiment a virtual pattern which has the same field strength for all elevations is used. In a second embodiment a slightly raised one-lobe virtual pattern is used.

The system permits comparatively error-free measurement of the elevation, even in very difficult terrain conditions in the vicinity of the runway and in extremely poor visibility conditions, as well as the selection of two different patterns depending on the accuracy and elevation desired.

An embodiment of the invention will now be described, by way of example, with reference to the accompanying drawings, in which:—

Fig. 1 shows a first real group pattern of a linear antenna array with 20 radiators or the corresponding virtual pattern which is used, e.g. to measure elevations greater than 2°;

Fig. 2 shows a second real group pattern of a linear antenna array with 20 radiators or the corresponding virtual pattern which is used, e.g. to measure elevations equal to or smaller than 6°, and

Fig. 3 shows a block diagram of an airborne receiver.

As mentioned in the introduction, the elevation is measured by the phase-difference method using a phase interferometer. If two radiators are used which are arranged one above the other, the illumination of the ground results in great measuring errors. To avoid these errors, two like radiator groups are employed instead of the two individual antennas. Each radiator group produces a strongly directional pattern, which will hereinafter be referred to as group pattern.

One of these two like group patterns which would be particularly favourable to the

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measurement of elevations above 2° is shown as a broken line in Fig. 1 and designated A. With the aid of a linear array consisting of 20 radiators spaced

$$d=\frac{\lambda}{2}$$

apart, and if the individual radiators were fed with suitable amplitude and phase, a group pattern according to curve B of Fig. 1 would be obtained which comes very close to the ideal pattern A. From the group patterns of two such linear arrays, the elevation could be determined by measuring their phase difference in an airborne station.

After this introduction, the invention will now be described. The invention uses radiator groups whose radiators radiate successively rather than simultaneously. Nevertheless, values are determined in the airborne station which would occur if the radiators radiated simultaneously.

The ground station (not shown) is located at the end of or beside the runway. It includes a vertical antenna array with 40 similar dipole radiators which are lined up parallel to each other. The spacing between the radiators is equal to one-half the operating wavelength λ. The radiators are successively connected to a transmitter and radiate pulses containing an r.f. oscillation whose amplitude and phase are equal for all radiators. Prior to each radiation cycle, a first pulse train is radiated via the first radiator.

In the receiver, the pulses are processed at the rate at which the radiators of the linear antenna array are connected. When the first pulse train appears, it is arranged that the pulse from the first radiator follows next, so that an unambiguous assignment of the received pulses to the radiators is obtained. If the pulse received from the first radiator is chosen as the reference pulse, the phases of the pulses received from all radiators can be measured relative to the phase of the reference pulse with the aid of a meter provided in the receiver. Likewise, the amplitudes of the received pulses can be measured relative to the amplitude of the reference pulse. For ease of explanation, it is assumed that there are no interferences—which is not true in reality. Then, the amplitudes all assume the value of the amplitude of the first pulse. For the purposes of explanation, this value is assumed to be 1.

Since each pulse can be unambiguously assigned to one radiator, a number couple consisting of magnitude (amplitude) and phase is thus obtained for each pulse in the receiver. Each number couple represents a complex number Z or a vector. Since the pulse coming from the first radiator is the reference pulse, the associated number couple always has the phase 0 for all receiver positions. The phases of the number couples for the pulses from the other radiators depend on the receiver position.

The number couples obtained in this way are stored in a store in the airborne station.

From the vectors derived from the 40 radiators, two groups are now formed in the receiver; for example, the vectors of the radiators 1 to 20 form one group, and those of the radiators 21 to 40 the other. However, the groups may also overlap. The vectors of each group are changed in magnitude and phase, and the sum of the changed vectors is then formed for each group. The change of the vectors in magnitude and phase is effected in the same way as the radiators would have to be fed to obtain the pattern B of Fig. 1. The absolute value of the sum is equal to the field strength which a receiver would determine in a group pattern as shown in Fig. 1, provided that the receiver is located at the same elevation. The phase of the vector sum is also equal to the phase of the field strength which a receiver would determine in a group pattern as shown in Fig. 1. Thus, in the airborne station, the magnitude and phase of the same field strength are determined as if a group pattern were present. If a vector sum S were determined for each elevation $\phi$ by the addition of the vectors, the absolute values of the vector sums for all angles $\phi$, plotted against $\phi$, would yield a curve which will hereinafter be referred to as virtual pattern. The term "virtual" expresses that this pattern is not really present in space. However, it is identical to the real group pattern shown in Fig. 1, curve B.

In both groups, the absolute values of the vector sums are equal at equal elevation. However, the vector sums of both groups differ in phase. The phase difference is a measure of the elevation. It can be calculated from the equation

$$P_F-P_0=2\pi\,.\,20\,.\,\frac{d}{\lambda}\,.\,\sin\phi \qquad (1)$$

where $P_0$ is the phase of the sum of the vectors of the pulses derived from the radiators 1 to 20 (group O), and $P_F$ is the phase of the sum of the vectors of the pulses derived from the radiators 21 to 40 (group F). Since the radiation centres of the groups O and F are $20\,d=10\,\lambda$ apart, the phase difference is ambiguous; this means that, for example, a determined value of $P_F-P_0=30°$ can, in reality, also be $30°+360°$ or $30°+720°$, etc.

To make the phase difference unambiguous, two auxiliary values are determined. For determining the first auxiliary value, a third group G is formed from the vectors of the

pulses received from the 2nd to 21st radiators. The vector sum of the 20 radiators, changed according to the same law as above, is formed, and its phase $P_O$ is determined. The distance between the radiation centre of group G and that of group O is

$$d=\frac{\lambda}{2}.$$

The first auxiliary value then follows from the equation

$$P_G-P_O=2\pi\cdot\frac{d}{\lambda}\sin\phi \qquad (2)$$

This equation is unambiguous because $P_G-P_O$ lies in the whole elevation range ($\phi$ between 0° and 90°) between 0° and 180°. If the phase difference is negative, the value is corrected by adding 360°.

For determining the second auxiliary value, a further group Z is formed from the vectors of the pulses received from the 5th to 24th radiators. Again, the sum of these 20 vectors, changed according to the same law as above, is formed, and its phase $P_Z$ is determined. The distance between the radiation centre of group Z and that of group O is $4\,d=2\,\lambda$. The second auxiliary value then follows from the equation

$$P_Z-P_O=2\pi\cdot 4\cdot\frac{d}{\lambda}\cdot\sin\phi \qquad (3)$$

The value determined with equation (1) is more accurate by a factor of 20 than the value determined with equation (2). This factor 20 is too great to resolve the ambiguity of the phase measurement $P_F-P_O$ in a single step because the values determined with equations (1) and (2) may be falsified due to multipath propagation. This is why the second auxiliary value is necessary.

Thus, the following relationship exists between the phase differences determined with the aid of equations (1) to (3):

$$P_Z-P_O=4\,(P_G-P_O) \qquad (4)$$

$$P_F-P_O=5\,(P_Z-P_O) \qquad (5)$$

These two equations are used to determine the unambiguous, accurate elevation value.

After the phase differences $P_G-P_O$ and $P_Z-P_O$, calculated from the measured vectors, have been substituted into equation (4), the value of $P_Z-P_O$ is increased by 360° as many times as is necessary to satisfy the equation in the best possible manner. The value of $P_Z-P_O$ obtained in this way as well as the value of $P_F-P_O$ calculated from the measured vectors are substituted into equation (5). The value of $P_F-P_O$ is then increased by 360° as many times as is necessary to satisfy equation (5) in the best possible manner. With the value of $P_F-P_O$ obtained in this way, the elevation $\phi$ is calculated with the aid of equation (1).

A description of the block diagram of the receiver of Fig. 3 will now be made. The r.f. pulses are received by an antenna 3; from there, they are applied through a tunable circuit 4 to the mixer 5, to whose other input an r.f. oscillation from an oscillator 6 is applied. The output of the mixer 5 is connected to a first i.f. unit 7. This unit is followed by a changeover switch 8, which, in the position shown, connects the first i.f. unit 7 to an oscillator 10. If the changeover switch 8 is in the other position, the first i.f. unit 7 is connected to a second i.f. unit 9, to whose output are connected an amplitude meter 11 and a phase meter 12. The output of oscillator 10 is connected to the second inputs of the amplitude meter 11 and of the phase meter 12. The outputs of the meters 11 and 12 are connected to a computer 13, whose output is connected to an indicator 14 of elevation. Also connected to the output of the first i.f. unit 7 is a device 15 for detecting the pulse train, for actuating the changeover switch 8, and for controlling the computer 13. When the device 15 detects the pulse train, it sends a signal to the computer 13 and puts the changeover switch into the position shown, so that the subsequent pulse from the first radiator is applied to the highly accurate oscillator 10 and synchronizes the latter with respect to amplitude and phase.

After the first pulse, the changeover switch 8 is changed to its other position, so that the following pulses are applied through the second i.f. unit 9 to the meters 11 and 12. The phase and the amplitude of the output signal of oscillator 10 are the measured quantities of the first pulse and serve as reference quantities for the measurement of the phases and amplitudes of the pulses from the second to the (n)th radiators. The amplitude and phase meters are known and, therefore, will not be explained herein detail.

The phase value $\phi_\nu$ and the amplitude value $A_\nu$ ($\nu=1\ldots n$) are stored in the computer store or in a separate store.

The read-in is controlled by a counter (not shown) which is advanced at the same rate as that of the connection of the radiators of the linear array and, when the pulse train appears, is restored to its initial position.

The amplitude values $A_\nu$ and the phase values $\phi_\nu$ determine the vectors $Z_\nu$ according to the equation

$$Z_\nu=A_\nu\cdot\exp(i\,\phi_\nu) \qquad (6)$$

where $i^2=-1$. The vectors are stored in a buffer storage.

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The vectors are now changed in groups and added into vector sums according to the following equations:

$$V_0 = \sum_{\nu=1}^{10} \frac{1}{2\nu-1} \left(Z_{10+\nu} \exp(-\alpha_\nu) + Z_{11-\nu} \exp(i\alpha_\nu)\right) = A_0 \exp(iP_0)$$

$$V_G = \sum_{\nu=1}^{10} \frac{1}{2\nu-1} \left(Z_{11+\nu} \exp(-i\alpha_\nu) + Z_{12-\nu} \exp(i\alpha_\nu)\right) = A_G \exp(iP_G)$$

$$V_Z = \sum_{\nu=1}^{10} \frac{1}{2\nu-1} \left(Z_{14+\nu} \exp(-i\alpha_\nu) + Z_{15-\nu} \exp(i\alpha_\nu)\right) = A_Z \exp(iP_Z)$$

$$V_F = \sum_{\nu=1}^{10} \frac{1}{2\nu-1} \left(Z_{20+\nu} \exp(-i\alpha_\nu) + Z_{21-\nu} \exp(i\alpha_\nu)\right) = A_F \exp(iP_F) \qquad (7)$$

where A is the amplitude, and P the phase, of the respective vector sum V.

For even-numbered values of $\nu$, $\alpha_\nu = 135°$; for odd-numbered values of $\nu$, $\alpha_\nu = 45°$.

From the group phases $P_0$, $P_G$, $P_Z$, and $P_F$, the phase differences are now determined with the aid of equations (4) and (5) as described above, and the elevation $\phi$ is calculated according to equation (1).

The absolute values of all four vector sums are equal, i.e.

$$S = |V_0| = |V_G| = |V_Z| = |V_F|.$$

If the absolute values for all receiver positions are plotted, the virtual pattern B of Fig. 1 is obtained. This curve very closely approximates to the ideal curve A. In the range between $\phi = -8°$ and $\phi = -60°$, the influences of the ground are almost completely eliminated through the good approximation to S=0. An exact computation of errors shows that the measuring error caused by the ground is smaller than $\pm 0.1°$ for $2.5° \leqq \phi \leqq 60°$ at any height of the array above ground. The ground is assumed to be plane, horizontal, and homogeneous, with $\varepsilon\nu = 15$. Vertical polarization is assumed.

If it is desirable to have equal or higher accuracy in the range below 2.5°, a pattern as shown in Fig. 2 is used. It is a one-lobe pattern whose direction of maximum radiation forms an angle of 6° with the horizontal line. This pattern would be obtained as a group pattern if, of the 40 radiators of the ground station, 20 radiators arranged side by side radiated simultaneously, the first radiator being fed with a phase $\alpha = -19°$, and the following radiators with a multiple of the angle $\alpha$ ($2\alpha$, $3\alpha$ . . . $20\alpha$) corresponding to their ordinal numbers (within the group) and with suitable amplitudes.

Since the radiators of the ground station do not radiate simultaneously, no group pattern is present, and the field strength of the group pattern which corresponds to the location of the aircraft is again simulated in the receiver.

The calculation operation is similar to that for the above-described determination of the elevation. First, the following vector sums are determined:

$$V_0 = \sum_{\nu=1}^{20} \left(1 - 0.5 \cos\left(\nu - \frac{1}{2}\right) \frac{4\pi}{n}\right) Z_\nu \exp(i\nu\alpha) = A_0' \exp(iP_0')$$

$$V_G = \sum_{\nu=1}^{20} \left(1 - 0.5 \cos\left(\nu - \frac{1}{2}\right) \frac{4\pi}{n}\right) Z_{\nu+1} \exp(i\nu\alpha) = A_G' \exp(iP_G')$$

$$V_Z = \sum_{\nu=1}^{20} \left(1 - 0.5 \cos\left(\nu - \frac{1}{2}\right) \frac{4\pi}{n}\right) Z_{\nu+4} \exp(i\nu\alpha) = A_Z' \exp(iP_Z')$$

$$V_F = \sum_{\nu=1}^{20} \left(1 - 0.5 \cos\left(\nu - \frac{1}{2}\right) \frac{4\pi}{n}\right) Z_{\nu+20} \exp(i\nu\alpha) = A_F' \exp(iP_F') \qquad (8)$$

where $n$ denotes the total number of radiators involved, in this case, forty.

The absolute values $A_O'$, $A_G'$, $A_Z'$, and $A_F'$ of the vector sums are equal and, calculated for all receiver positions, yield the virtual pattern of Fig. 2.

From the phases $P_O'$, $P_G'$, $P_Z'$ and $P_F'$, the elevation is again determined, as described above, with the aid of equations (4), (5), and (1).

At heights of the linear antenna array above ground between $\lambda$ and $20\lambda$ and at elevations from 1.6°, this method has a system error of ±0.05°.

The airborne receiver is advantageously designed to switch from one mode of operation to another at 6° elevation, or vice versa.

WHAT WE CLAIM IS:—

1. A system for the measurement of elevation by the measurement of phase-difference in which, at a ground station, n equally spaced radiators of a vertical linear antenna array cyclically and successively radiate r.f. pulses with equal magnitude and equal phase, one pulse train being radiated prior to each radiation cycle, and in which, at an airborne station, the phase and amplitude of the r.f. oscillations of each pulse in each cycle are measured relative to one of the pulses, at least two different groups being formed each containing m successive received pulses (where m<n), wherein, in each group, the phase and amplitude of each pulse are changed, the changes for corresponding pulses of all groups being the same, the vector sum of the changed pulses of each group is determined, and the elevation is determined from the phase differences of the said vector sums.

2. A system as claimed in claim 1 in which the measured values of the pulses are so changed that the absolute value of the vector sum is equal to the field strength which would occur at the place in which the receiver is located if a group pattern were present whose field strength were approximately equal for all elevation angles.

3. A system as claimed in claim 1 in which the measured values of the pulses are so changed that the absolute value of the vector sum is equal to the field strength which would occur at the place in which the receiver is located if a group pattern with raised main lobe were present.

4. A system as claimed in any one of the preceding claims, in which four pulse groups are formed, first and second groups being used for the measurement of an ambiguous phase difference corresponding to portions of the ground station antenna array whose radiation centres are relatively far apart, and in which, for obtaining unambiguous information, use is made of the phase differences between the first mentioned group and two further groups whose equivalent radiation centres on the antenna array lie nearer the equivalent radiation centre of the first group than does the equivalent radiation centre of the second group.

5. A system for use in the measurement of elevation substantially as herein described with reference to the accompanying drawings.

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2 SHEETS    *This drawing is a reproduction of the Original on a reduced scale*
Sheet 1

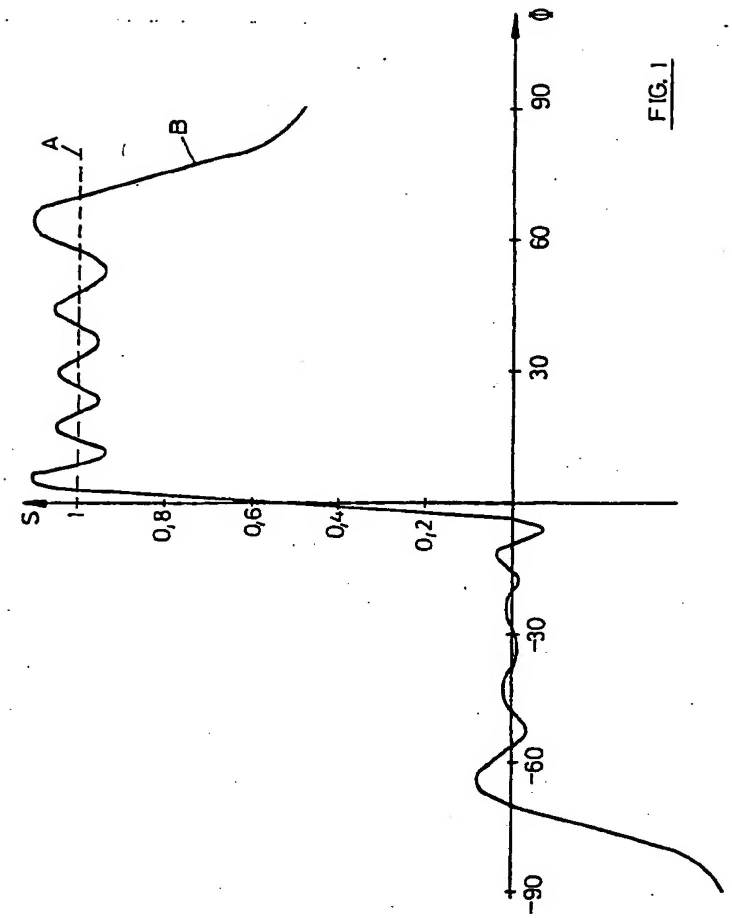


FIG. 1

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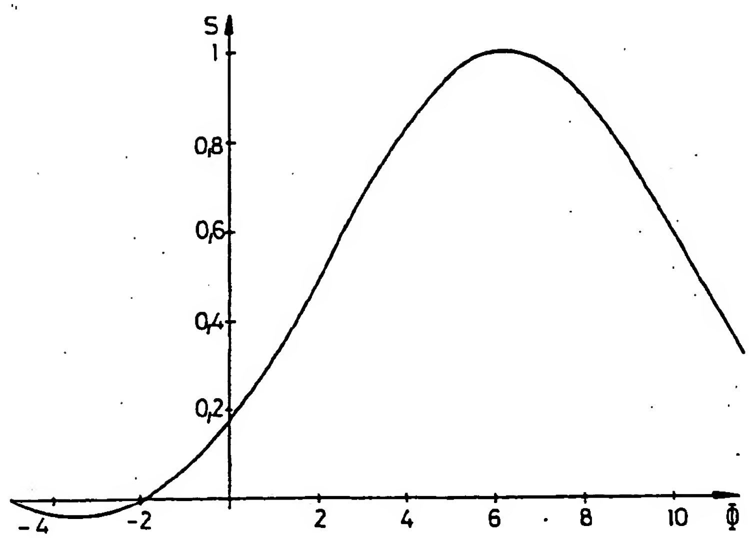


FIG. 2

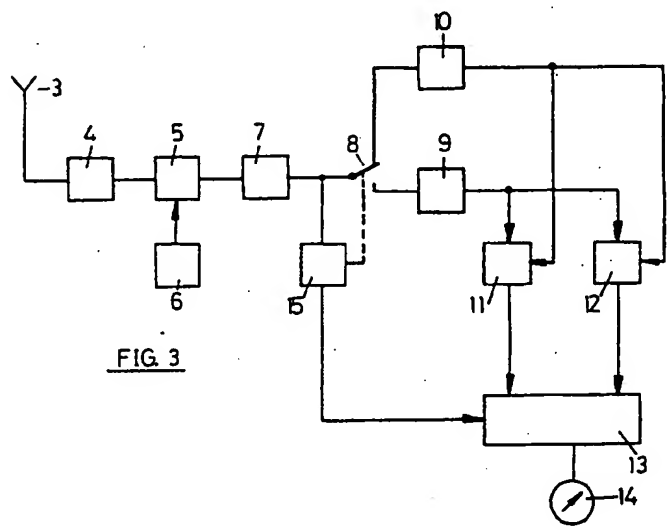


FIG. 3